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INVESTIGATIONS ON TRAVELLING IONOSPHERIC DISTURBANCES (TID'S) BY THE CW DOPPLER PHASE-PATH SOUNDING ARRAY

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TELEDYNE ISOTOPES

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13. ABSTRACT

Travelling ionospheric disturbances in the ionized regions of the earth's atmosphere have been investigated using a CW doppler (phase-path) sounding array. A description of wave characteristics such as periods and wavelengths for medium scale TID's is given. An apparent correlation between TID's and occurrence of sporadic E was examined in the light of internal atmospheric gravity wave theory. The results of the present investigation were compared with those of earlier results. It can be concluded from this study that near the solstices, TID's in both hemispheres travel in approximately the same direction, away from the pole. Near the equinoxes, TID's in the Northern Hemisphere travel approximately in the westward firection, while those in the Southern Hemisphere travel eastward.

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Ionospheric irregularities						

TELEDYNE ISOTOPES

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TELEDYNE ISOTOPES

INVESTIGATIONS ON TRAVELLING IONOSPHERIC DISTURBANCES (TID'S) BY THE CW DOPPLER (PHASE-PATH) SOUNDING ARRAY

1. Introduction

The dynamical behavior of the upper atmosphere produces several phenomena, such as wave forms in noctilucent clouds, irregular structure in wind systems near the base of the thermosphere, and variations in the vertical temperature structure profiles. These phenomena can be partly accounted as manifestations of internal atmospheric gravity waves. It is also broadly interpreted by several investigators that ionospheric irregularities such as sporadic E ionization, spread F ionization and travelling ionospheric disturbances are created and propagated due to the presence of internal atmospheric gravity waves. The dynamical state of the ionosphere is distinctive in three respects: tidal oscillations achieve their maximum amplitude there and exceed the prevailing winds; irregular winds, subject to rapid variation with height, attain an equal intensity; and the turbulent regime of lower levels gives way to a nonturbulent domain above. Extensive observational data, using meteor trail and rocket vapor trail techniques, of winds and tides at ionospheric heights are available. These investigations reveal strong seasonal variations in the tidal wind, both diurnal and semidiurnal, at heights near 90 km. Atmospheric oscillation with periods usually no greater than an hour are termed as atmospheric gravity waves. These waves are presumably responsible for perturbations in neutral and ionozed structures of the atmosphere in the mesosphere and in the lower thermosphere.

The electron density distribution in the ionosphere exhibits perturbations of varying intensities and spatial dimensions. If one considers the medium as a series of isoionic contours of surfaces of constant ion density, then the presence of such perturbations produces curvatures and tilts of these surfaces, resulting in diffraction, refraction and reflection processes of radiowaves traversing the medium. When these disturbances travel horizontally in the ionosphere their radiowave pattern on the ground moves correspondingly. These disturbances are broadly classified as travelling ionospheric disturbances or TID's and they frequently appear in the form of propagating wave-like motions ranging in magnitude from very large scale disturbances with periods of the order of an hour that travel thousands of kilometers (Chan and Villard, 1962) to wave effects with periods near 1 minute probably locally generated (Davies and Baker, 1969). Between these extremes are types of wave-like motions with periods in the range of 10 minutes to 1 hour and phase velocities of 100-200 m sec^{-1} called "medium-scale" disturbances (Georges,1967), which occur frequently and have been widely observed.

In order to identify ionospheric waves produced by nuclear explosions, it is important to have a fair understanding of the ionospheric background motions. Therefore, it was necessary to investigate the naturally occurring wave trains on doppler records. The origin of these naturally occurring wave trains can be in general hydromagnetic or hydrodynamic. During the last contract period correlations between doppler frequency variations and geomagnetic micropulsations, in the period band 0.5 min to 5 min, have been reported (Montes et al, 1970). During this contract period we have initiated an investigation of naturally occurring long period wave trains (10-30 min) under

magnetically quiet conditions. It is of interest to study the characteristics of these natural wave trains (medium scale TID's) as they are controlled by the atmospheric structure between 90-300 km.

Earlier work on TID's provided information on speeds and directions. A clear description of wave characteristics such as periods and wave lengths is not available and it is this problem which is investigated here. An attempt has been made to provide a statistical description of the wave characteristics of medium scale TID's from the data collected using an array of CW doppler (phase-path) sounders. Some TID characteristics were investigated and an apparent correlation between TID's and occurrence of sporadic E has been examined in the light of internal atmospheric gravity wave concepts. The results of this work are compared with those of earlier investigations. A summary of the results and suggestions for future work are presented at the end of the report.

2. Earlier Work on TID's

Pierce and Mimno (1940) were the first investigators to notice the presence of TID's in the F2 region of the ionosphere. From comparatively little evidence they built up a description of the disturbance as observed at one receiving site. Later, Wells et al (1946) found evidence which led them to believe that a vertical transport of ionization clouds exists in the F2 region. TID's were also studied by Beynon (1948) during sunrise and between 1900-0500 LMT in the winter of 1942-43. The average speed reported by him was 120 m sec^{-1} and the direction of travel was westward during sunrise hours. Munro (1950, 1953a,b, 1958) suggested that these wave-like

disturbances seen on ionograms may be due to the disturbances in the neutral atmosphere itself, taking the form of travelling pressure waves which cause a redistribution of ionization. These quasi-periodic changes of the electron density, especially in the F2 region, were explained by Martyn (1950) as being due to horizontally travelling atmospheric cellular waves of the type investigated by Lamb (1909). Beynon and Thomas (1954) found that an increase in TID phase velocity was followed by an increase in geomagnetic K index. Munro's experiments were repeated at Perth, West Australia by Price during the daytime in winter and summer of 1950-1952. The results of this experiment (Price, 1953; 1955) indicated that the phase velocities ranged from 90 - 330 m sec^{-1} and that the direction of travel varied from 0° to 60° E of N during winter and in the range 90° to 180° E of N during summer. Bramley and Ross (1951) and Bramley (1953) used the same technique, and obtained velocities in the range 35 - 330 m sec^{-1}. Sen (1949) and Osborne (1955) in Singapore, and Skinner et al (1954) in Ibadan also observed perturbations in H.F. records at low latitudes which they attributed to TID's.

Using vertical incidence soundings of the ionospheric F2 regions from an array of three stations separated 200 km apart, Thomas (1959) obtained velocities of propagation by studying corresponding fluctuations in the critical frequency and the equivalent height of reflection, at a particular height, on all three stations. The measured velocities ranged from 40 - 280 m sec^{-1} and the direction of travel was mainly SE. Using another station at 650 km from the main array, he showed that TID's travelled with little change in direction and speed. He obtained a positive vertical gradient of 1 m sec^{-1}/km of velocity within the F2 region. The vertical gradient was larger in winter than in summer.

Many investigators have reported the existence of large travelling disturbances (TID's) detected by such methods as vertical soundings, doppler phase-path soundings and H.F. backscatter techniques. DuCastel and Faynot (1964), utilizing simultaneous observations from ground network of rapid sequence ionosondes and topside soundings from the Alouette Satellite, detected large disturbances usually moving southward with an apparent speed of 180 m sec^{-1}. They further postulated that these irregularities originate at high latitudes and move toward equatorial regions. From the occurrence of irregularities in the Faraday rotation period of satellite signals, Liszka and Taylor (1965) presented some tentative evidence that large irregularities in total electron content, which occur in patches with horizontal scales of 1000 km, may be generated in the auroral zone and then propagate southward with velocities of a few hundred meters per second. Recently, Thome (1964) and Thome and Rao (1968) have reported the results of a study of large scale travelling disturbances in the ionosphere using a combination of incoherent backscatter sounding technique and phase-path doppler technique. They concluded that the large TID's were propagated by atmospheric gravity waves and that the auroral electrojet was the most probable energy source. Hunsucker and Tveten (1967) reported large TID's using high-resolution H.F. backscatter sounder. The direction of motion was predominantly toward the southeast and the horizontal speeds were in the range 100 - 170 m sec^{-1}.

3. TID Observations Using the CW Doppler (phase-path) Technique

Travelling ionospheric disturbances in the ionized regions of the earth's atmosphere have been observed by various methods for several decades. Among the frequently employed methods are conventional ionosonde, incoherent backscatter, high frequency ground backscatter radar and phase sounders. There are two kinds of phase sounders. One uses pulse sounding and the other uses CW sounding. In the present investigation of TID's an array of CW doppler (phase-path) sounders were used to monitor and record several TID's of various characteristics.

Basic Theory of CW Doppler (phase-path) Soundings

When a radiowave of constant frequency f is transmitted from a stable transmitter and received via ionospheric reflection, it is observed that the frequency of the received signal fluctuates slightly. The frequency fluctuations are due to changes in the phase-path of the radiowave. The relation connecting frequency fluctuations and phase-path variations in the absence of the earth's field can be expressed as (Davies 1962, and Davies and Baker 1965).

$$\Delta f = \frac{f}{c}\, dp/dt$$

where

f = transmitted frequency
c = speed of light in free space

$p = \int \mu ds$ = phase-path

and μ is the refractive index along the ray path s. The phase-path, hence Δf, are functions of both μ and s. Consequently a frequency shift can result from either two effects, or a combination of both.

(1) Change in the ray path (s) caused by change in the height of reflection.

(2) Change in the refractive index (μ) along the path caused by change in electron density below the level of reflection.

Considering the first case, if we assume mirror-like reflection at a height h, with no changes in refractive index below h, then

$$\frac{dp}{dt} = -2\,\frac{dh}{dt}$$

$$\Delta f = \frac{2f}{c}\,\frac{dh}{dt}$$

and so far a given rate of change of reflection height

$$\Delta f \propto f$$

In the second case, if we assume a constant height of reflection and change in electron density below the level of reflection, then in general

$$\Delta f \propto 1/f$$

In reality the situation is more complicated, but the important point is that the variation of Δf with f gives an indication of the cause of the doppler shift Δf. An important case where doppler shifts are not dominated by reflection heights is that of solar flare ionization enhancements due to X-rays.

The sensitivity of the doppler technique in its present state of development is about 0.1 Hz, that is, phase-path changes as small as 1/10 of a radiowave length per second can be measured. At 4 MHz, this corresponds to $dp/dt \simeq 7.5\ \text{m sec}^{-1}$.

The CW doppler (phase-path) sounder system was of the same type as that described by Davies (1962) with some modifications. A significant difference between Davies system and the Teledyne Isotopes system is in the

presentation of data. In our system the doppler signal is digitized and stored in digital magnetic tape whereas in the Davies system the signal is recorded on magnetic tape in analog form. The digital form of recording data allows the use of modern digital processing techniques such as beam forming, cross correlation, power and cross spectral analyses, digital filtering and contour plotting. The details of the experimental setup, array design and data processing techniques have been described in a previous report (Montes et al, 1970).

4. Ionospheric Motions and Irregularities

Extensive global studies of perturbations in both E and F regions have been made by the so-called "spaced receiver method" due to Mitra (1949). A summary and review of the results from the spaced receiver method through the IGY-IGC period were reported by Rao (1965,1966) and Rao and Rao (1964,1965). Kochanski (1966) analyzed 54 sodium cloud firings using rockets and isolated components due to wind and gravity waves. He compared the results with the ionospheric spaced receiver technique results (ionospheric drifts) of Rao (1965,1966). These results are presented in Tables 1 and 2. It can be seen from the tables that in the height ranges 100-115 km the motions of neutral and ionized components appear to be quite similar. Periodic variation detected in ionospheric drift data suggest that the amplitudes of 24-hour and 12-hour tides are the same, with slight preponderance of the former. Similar results were obtained by Elford and Roper (1965), who applied spectrum analysis to sodium cloud data, and found that spectral peaks for 24-hour and 12-hour tides are roughly equal. Apart from diurnal and semidiurnal tides in the wind data, Hines (1960) pointed out the irregular fluctuations, whose periods are in the range 10-120 minutes, seen on wind and temperature profiles in the 80-300 km

TABLE 1

IONOSPHERIC DRIFTS COMPARED WITH SODIUM CLOUD WINDS

A. Apparent Ionospheric Movements (Rao and Rao, 1964, 1965)

		E Region		F2 Region	
Station	Latitude	Observed Mean Speed, V m/sec	Resultant Vector, S_r	Observed Mean Speed, V m/sec	Resultant Vector, S_r
Gorky	56°N	---	----	97	ESE 25
De Bilt	52°N	90	SSE 07*	---	---
Simeiz	44°N	---	----	115	E 11*
Ashkabad	38°N	---	----	74	N 41
Yamagawa	31°N	78	WNW 52	80	NW 50
Waltair	18°N	86	NNW 23	100	WSW 26
Willington	41°S	80	WSW 29	---	---

B. Sodium Cloud Winds (Kochanski, 1966)

		100-115 km Region		155-160 km Region	
Station	Latitude	Observed Mean Speed, V m/sec	Resultant Vector, R_r	Observed Mean Speed, V m/sec	Resultant Vector, R_r
Ft. Churchill	59°N	75	ESE 41	---	---
Sardinia	40°N	66	NNE 39	95	NNE 85
Wallops Is.	38°N	69	NNW 26	82	N 60
Eglin	30°N	77	ENE 23	72^e	---

e Extrapolated

* Too low, probably because of the cancellation of components of the opposite sign

TABLE 2

COMPARISON OF DIURNAL AND SEMIDIURNAL COMPONENTS OF SODIUM CLOUD WINDS AND IONOSPHERIC DRIFTS

Data for Yamagawa are apparent ionospheric movements (drifts) in the E-region and represent the vector sum of 'steady components' and vectors of 24-hour and 12-hour periodic components. Data for Wallops Islands and Eglin are for 100 to 115 km layer and represent sodium cloud winds.

Station	Summer 6 A.M.	Summer 6 P.M.	Resultant Vector of 6 A.M. + 6 P.M.	Winter 6 A.M.	Winter 6 P.M.	Resultant Vector of 6 A.M. + 6 P.M.
Yamagawa	273°	276°	275°	040°	088°	068°
$V(m\ sec^{-1})$	31	47	39	25	32	26
Wallops Is.	267°	315°	290°	359°	041°	021°
$V(m\ sec^{-1})$	25	26	23	29	29	26
Eglin	069°	296°	055°	356°	077°	026°
$V(m\ sec^{-1})$	44	14	18	36	23	23

region and argued that these fluctuations are due to atmospheric internal gravity waves propagating at these altitudes. The observed time scales for the irregular wind structure (~2 hr) lie in the gravity wave range. He further argued that several ionospheric phenomena such as sporadic E, spread F irregularities, ionospheric drift and TID's can be easily explained using the gravity wave interpretation.

4.1 Travelling Ionospheric Disturbances

The TID's are one aspect of several ionospheric motions and irregularities. From earlier work and his investigations, Georges (1967) classified and identified four distinct types of motions all of which were attributed to the effects of atmospheric waves that propagate to ionospheric heights from below. Two are of the kind that were previously called simply "large travelling disturbances". One, which Georges (1967) called "very large" usually follows large magnetic storms, the other is the kind Munro (1950) observed extensively in the daytime with the fixed frequency pulse sounders, called "medium scale" disturbances. A third kind of wavelike disturbance was geographically localized, was not correlated with geomagnetic or solar activity, and had a characteristic period of 3 minutes. This wavelike disturbance was correlated with severe weather activity in the troposphere (Georges 1968, Davies and Baker 1968). The fourth class of motion studied by Georges was due to random electron density fluctuations characteristic of "quiet" periods and sometimes attributed to ionospheric drifts. In this report, preliminary results of the investigation of "medium scale" TID's are given. Throughout this work a "medium scale" TID is defined as an ionospheric disturbance travelling with phase velocities of H.F. 100-200 m sec $^{-1}$ and periods of 8-30 minutes.

Hooke (1968) has investigated the passage of gravity waves at F region levels and determined the effects on the rates of ionospheric dynamical processes, photoionization processes and chemical loss processes. He also assessed the relative importance of each of these effects in the production of ionospheric irregularities by internal atmospheric gravity waves. The following were his main findings. The principal effect of gravity wave motions of the neutral gas at F region levels was to impart the motions of neutral gas to ions parallel to field lines through collisional interactions. Waves of moderate amplitude (including motions of the neutral gas of the order of 20 m sec $^{-1}$) were capable of producing large TID's. Changes in the rates of photoionization seem to play a significant role in the daytime gravity wave production of F region irregularities. Gravity wave induced changes in the values of recombination and loss coefficients in F region levels appear to be quite small. Following the arguments and theoretical computations by Hooke (1968) we assumed in the interpretation of CW doppler (phase-path) data in terms of acoustic gravity waves, that the mechanism for the interaction between atmospheric waves and ionization preserves such wave characteristics as phase velocity, group velocity, period and wave front.

4.2 Data and Method of Analyses

CW doppler data taken from October 1969 - February 1970 were characterized by certain events which represent a distinct class of travelling ionospheric disturbance. These events have a quasi-period range from 8 min to 24 min, the doppler frequency shifts are 1 to 4 Hz peak to peak, and the disturbances usually exhibit two and three sinusoidal cycles that are shifted in time on the traces corresponding to the various radio paths. For detection and further detailed analysis of TID signatures over a background doppler variation the following criteria was adopted.

(1) All radio transmission signals should be reflected from the same reflecting height. In this case the reflections are from F region of the ionosphere.

(2) Similar characteristics and periods should be seen on all the channels.

(3) Signal to noise ratio should be good in all the channels.

When computing the propagation characteristics of TID care should be exercised in selecting the time window for computing cross correlation coefficients. A good statistical estimate of the parameters can be obtained by taking large time windows. On the other hand, the ionosphere is dynamic in nature and large diurnal variations are often noticed on electron density perturbations, and as such the time windows should not be too large to include the diurnal changes. In the case of medium scale TID's the signature (or signal) lasted between 2 to 5 hours. For periods between 10-20 minutes, about a 2-hour window seems to give a good estimate of cross correlation coefficients and also represents ionospheric conditions minimizing diurnal changes. When the TID event lasted more than two hours, cross correlation coefficients for each two-hour window were computed for the entire TID event and phase velocities were deduced for each two-hour window. If the phase velocities for all the windows for an event were within reasonable agreement ($\pm$ 15 m sec $^{-1}$), then an average phase velocity for the event was computed, otherwise it was rejected.

The cross correlation functions ρ_{34}, ρ_{35} and ρ_{45} between the station pairs Catskill-Thornhurst, Catskill-Westwood and Thornhurst-Westwood respectively, were computed. The phase velocity was calculated from the following equations using the station geometry as shown in Figure 1, and the time delays derived from the cross correlation analysis

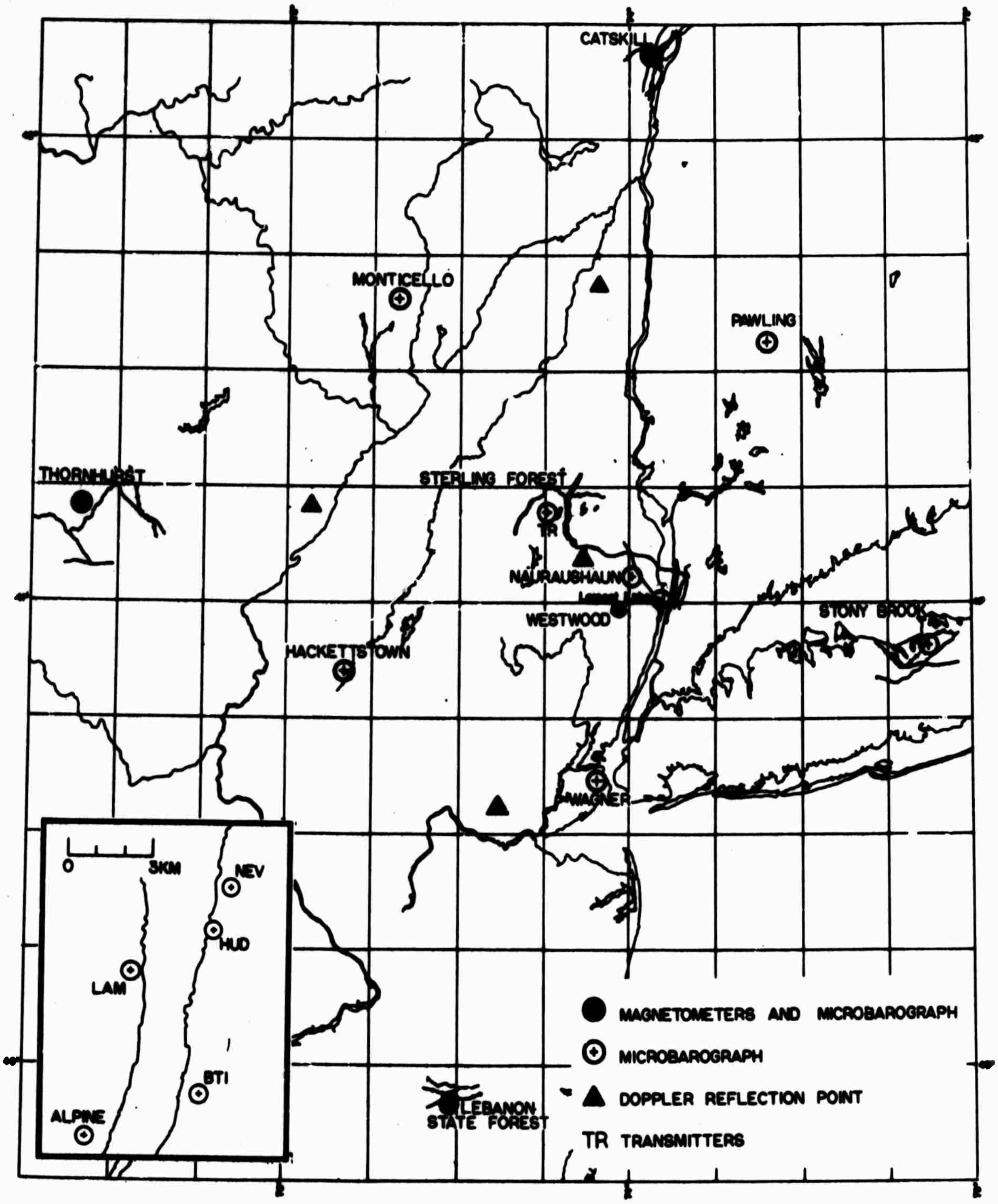

Fig. 1. Map showing the geographic distribution of the stations of the Teledyne Isotopes array.

$$\tan\theta = \left(\frac{X34}{X35}\right)\left(\frac{\tau 35}{\tau 34}\right)\frac{1}{\sin\alpha} - \cot\alpha$$

$$V = \left(\frac{X34}{\tau 34}\right)\cos\theta = \left(\frac{X35}{\tau 35}\right)\cos(\alpha - \theta)$$

where

X_{34} and X_{35} are the ionospheric reflection point distances between stations Catskill-Thornhurst and Catskill-Westwood respectively,

τ_{34} and τ_{35} are the corresponding time delays,

α is the angle between the paths joining Catskill-Thornhurst and Catskill-Westwood,

θ is the direction of propagation of the disturbance measured anti-clockwise from the line joining the stations Catskill-Thornhurst,

and V is the estimate of the horizontal phase velocity.

5. Results of the Present Investigation

For all the TID events taken during the period October 1969 through February 1970, the velocity and direction have been computed and the results are presented in Table 3. Typical TID's are shown in Figures 2 through 5. The velocities of all TID events were plotted against local time (Eastern Standard Time) and a smooth curve was drawn through the cluster of points as shown in Figure 6. It can be seen that most of the TID events occurred between 1500-2000 hours local time which correspond to pre-sunset, sunset and post-sunset conditions. It can also be noticed from the figure that the TID phase speeds during midnight are high compared to daytime and sunset time TID events. The directions of all TID events have also been plotted against local time, as shown in Figure 7, to study the diurnal variation of the direction of heading

TABLE 3

PHASE VELOCITY AND DIRECTION OF TID'S

Date	Time (EST)	Phase Velocity (m sec^{-1})	Direction (deg.)
10-3-69	1730	150	170
10-5-69	1800	181	279
10-5-69	1900	140	225
10-6-69	0000	284	346
10-6-69	1900	173	234
10-8-69	2300	152	329
10-20-69	1700	170	222
10-20-69	1830	230	228
10-24-69	0100	525	340
10-25-69	0500	73	330
10-25-69	1700	150	228
10-25-69	1900	205	226
10-26-69	2100	345	226
10-27-69	1700	215	230
10-28-69	1900	187	230
10-29-69	1830	180	235
10-30-69	1930	155	235
10-31-69	0100	365	353
11-2-69	1600	165	235
11-3-69	0700	25	135
11-4-69	1500	200	235
11-7-69	0100	525	165
11-12-69	1800	120	255
11-12-69	2000	125	268
11-13-69	2000	120	275
11-14-69	1800	160	230
11-14-69	1900	75	290
11-14-69	2300	155	355

TABLE 3 (continued)

Date	Time (EST)	Phase Velocity (m sec^{-1})	Direction (deg.)
11-20-69	1930	210	175
11-22-69	1600	220	225
11-23-69	1700	257	205
11-23-69	1900	240	235
11-24-69	0800	167	120
11-24-69	1900	125	250
11-24-69	1630	185	120
11-25-69	1600	205	225
11-27-69	1500	95	217
11-29-69	1500	95	220
11-30-69	1600	160	230
12-2-69	1830	170	185
12-2-69	2030	230	200
12-3-69	1000	105	225
12-11-69	1600	118	155
12-18-69	1700	150	200
12-19-69	0300	280	250
12-20-69	0800	138	178
12-21-69	0730	140	50
12-25-69	0830	138	180
1-1-70	1900	370	300
1-13-70	0400	212	116
1-13-70	0800	255	220
1-16-70	0300	125	94
1-21-70	1800	243	230
1-21-70	2000	330	210

TABLE 3 (continued)

Date	Time (EST)	Phase Velocity (m sec-1)	Direction (deg.)
1-22-70	2000	240	230
1-29-70	2100	150	187
1-30-70	1800	260	250
2-5-70	1800	240	230
2-5-70	1900	115	200

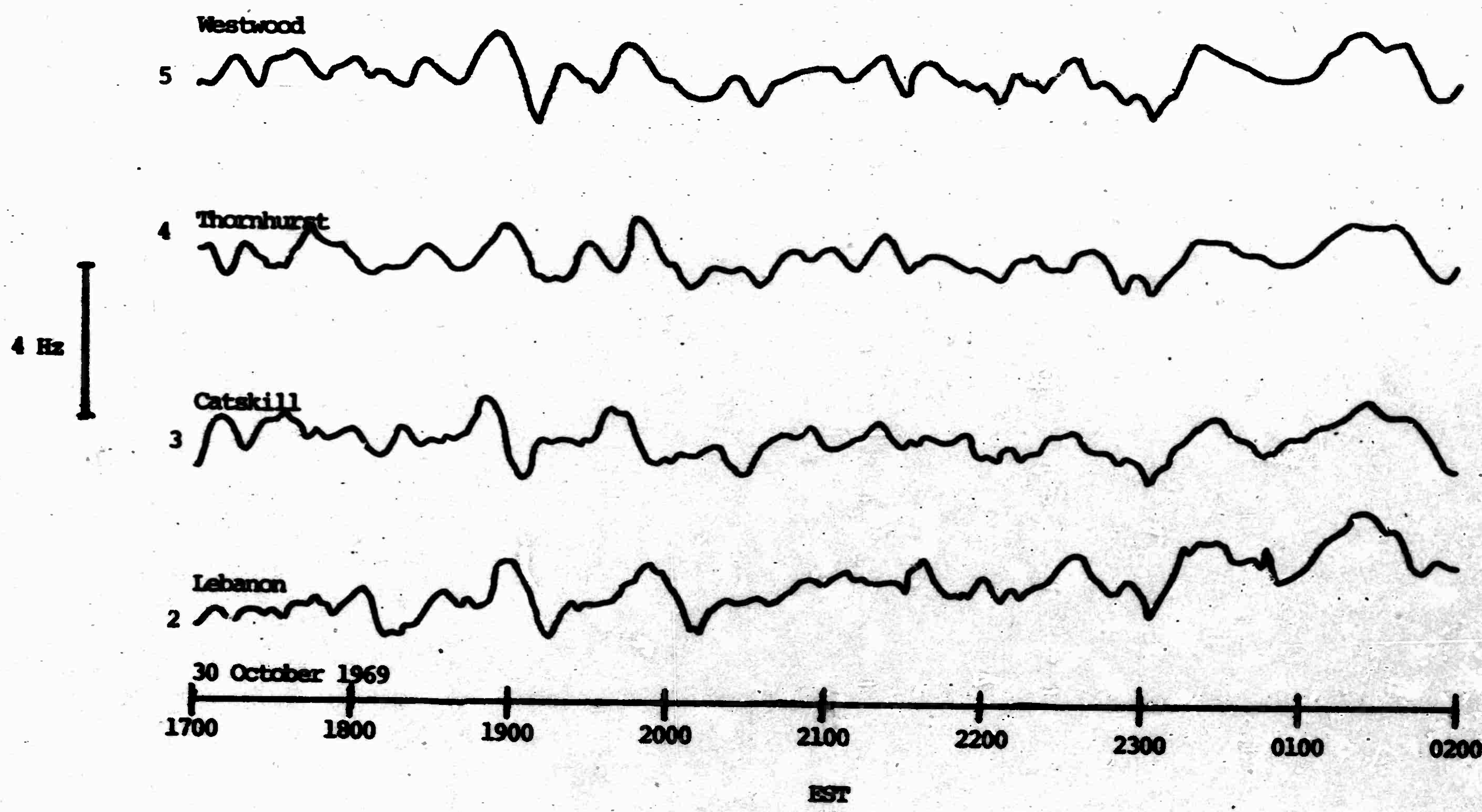

FIGURE 2. Typical TID's. Seen on Doppler Array.

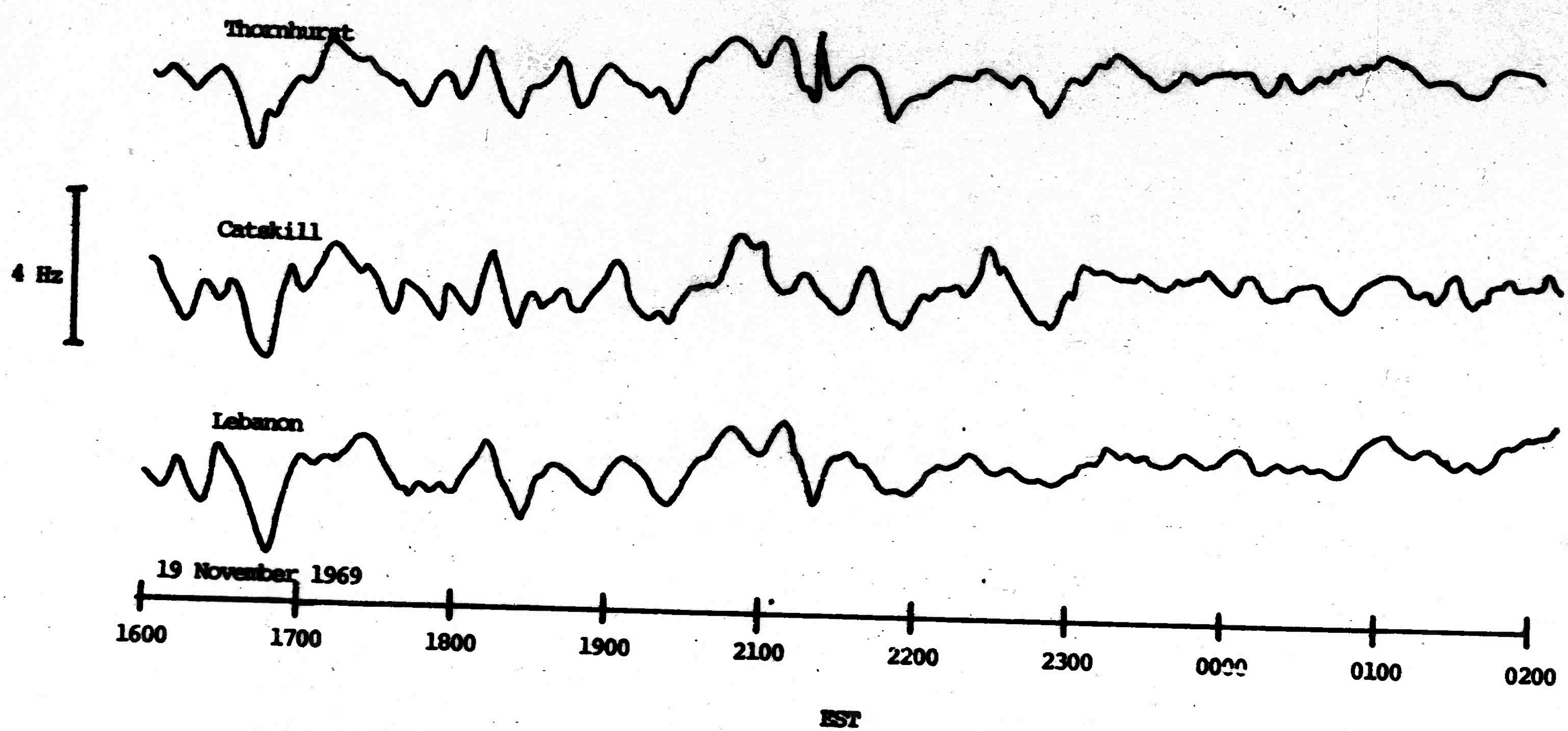

FIGURE 3. Typical TID's. Seen on Doppler Array.

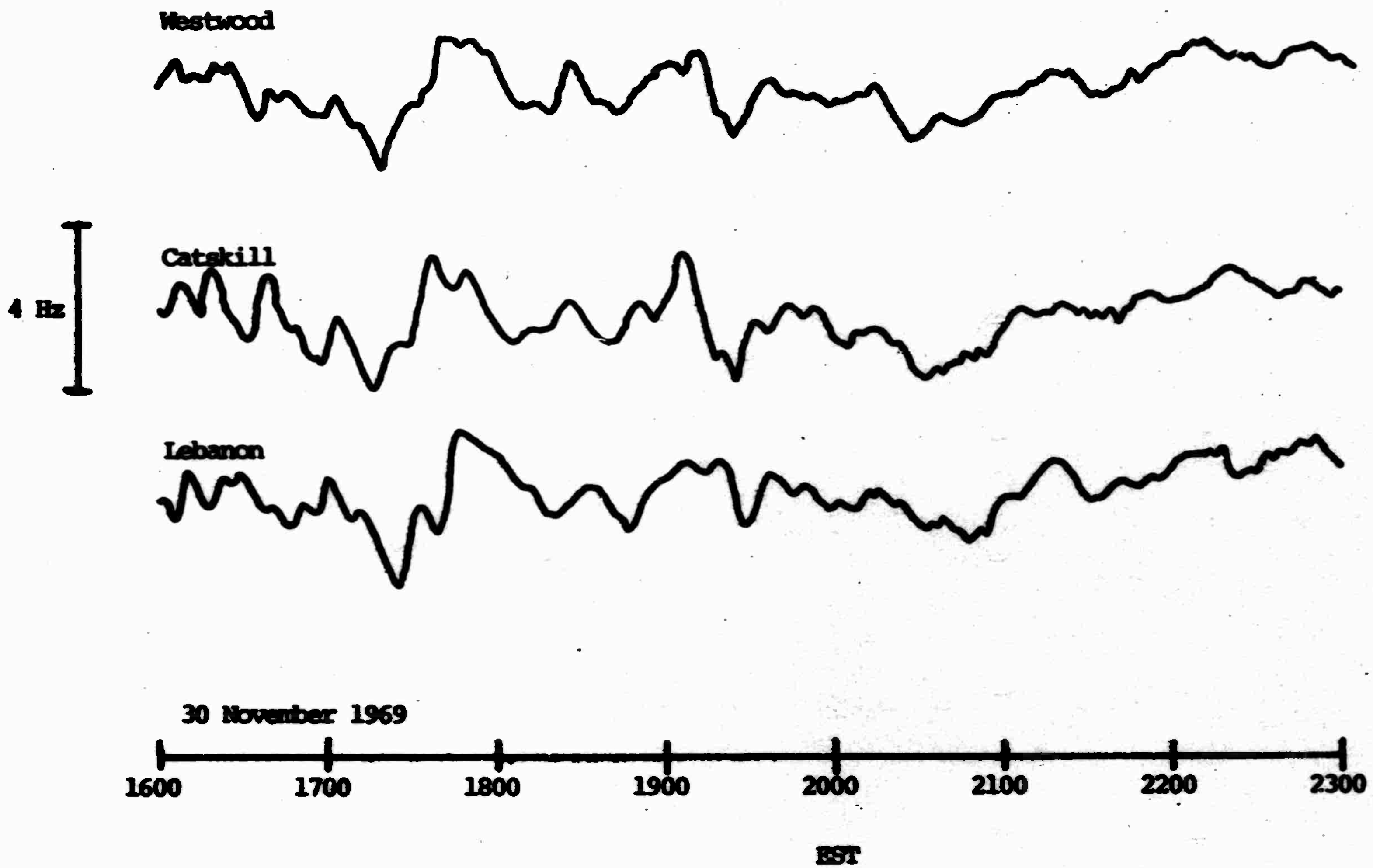

FIGURE 4. Typical TID's. Seen on Doppler Array.

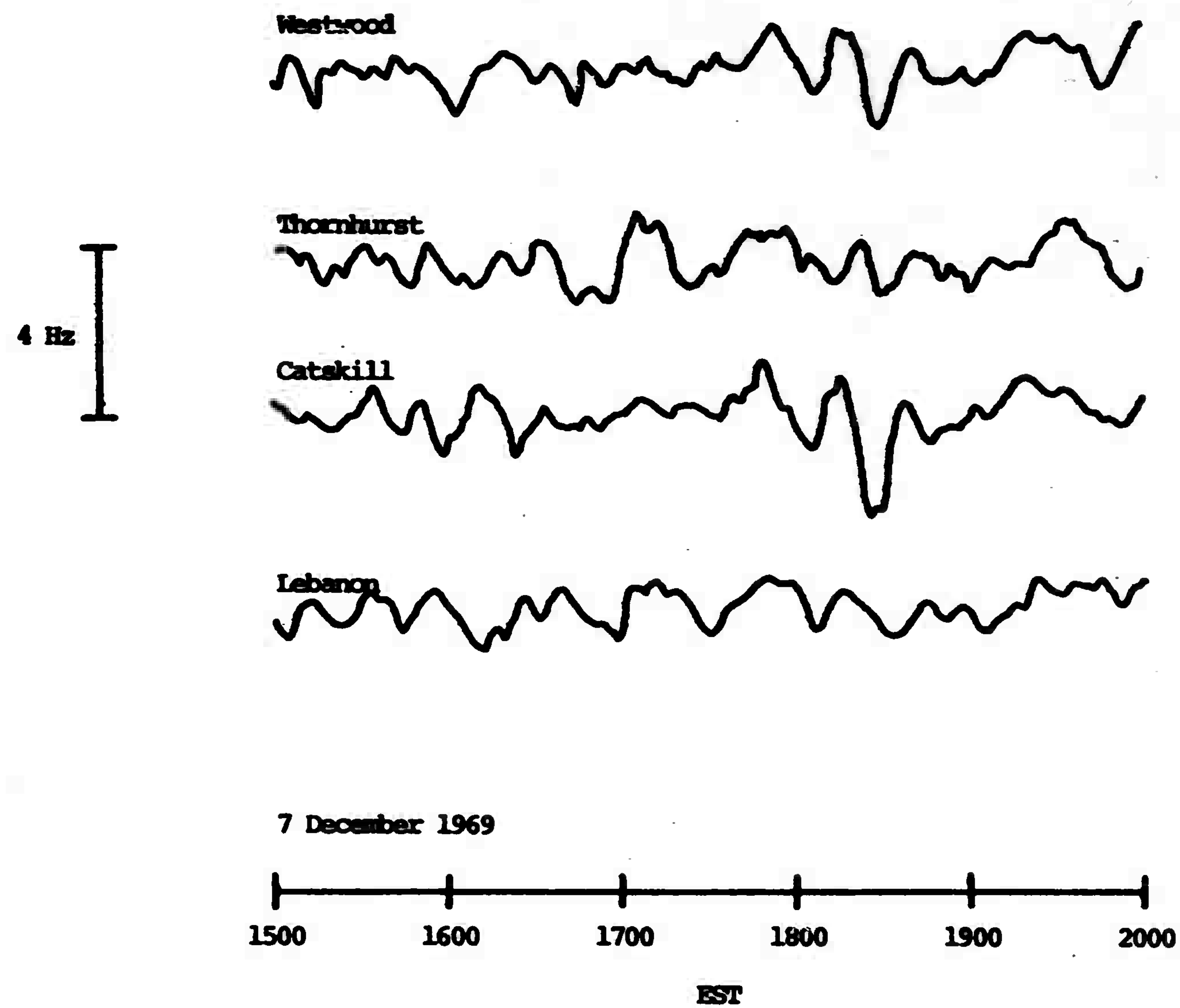

FIGURE 5. Typical TID's. Seen on Doppler Array.

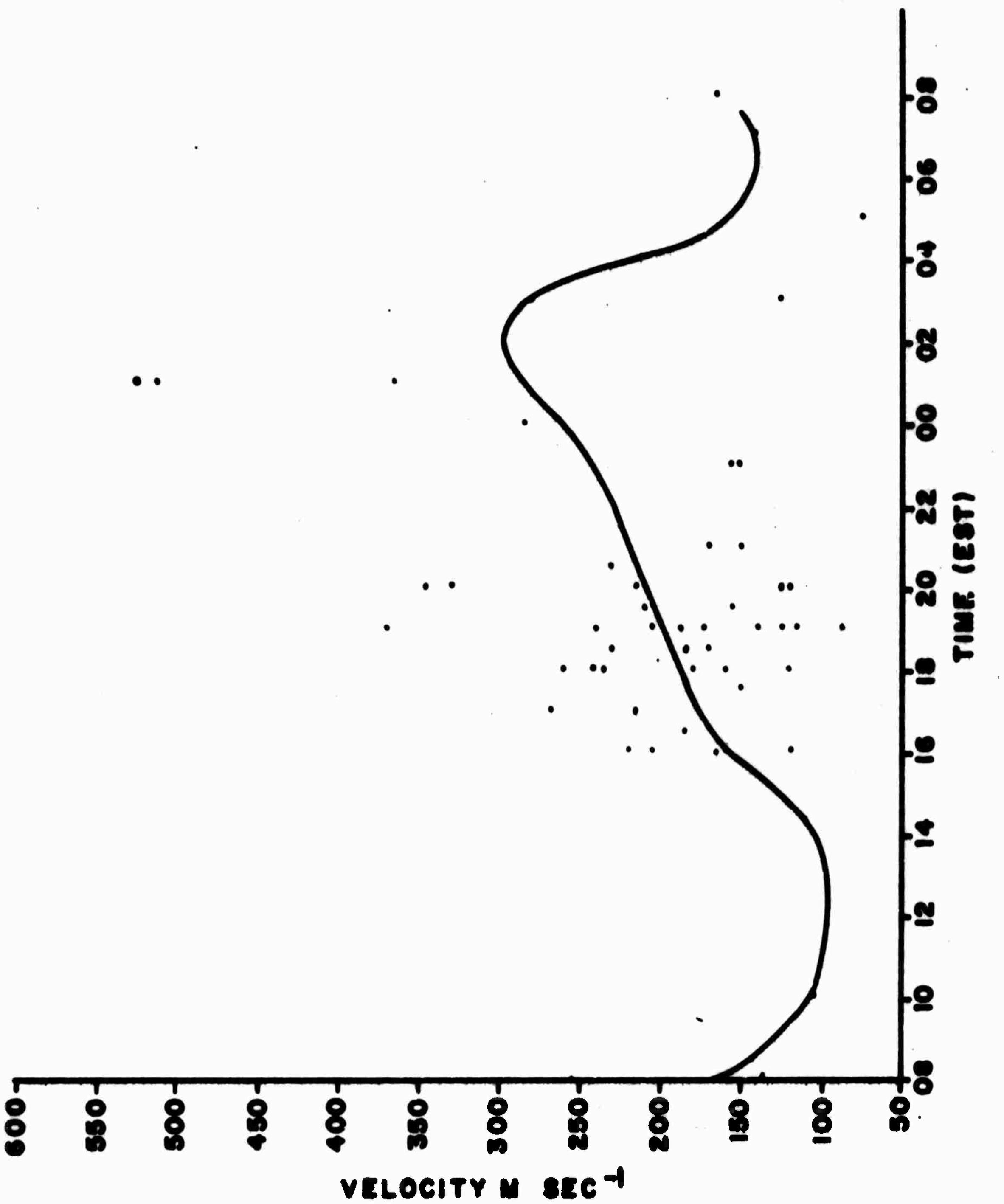

FIGURE 6. Diurnal Variation of TID Phase Velocities.

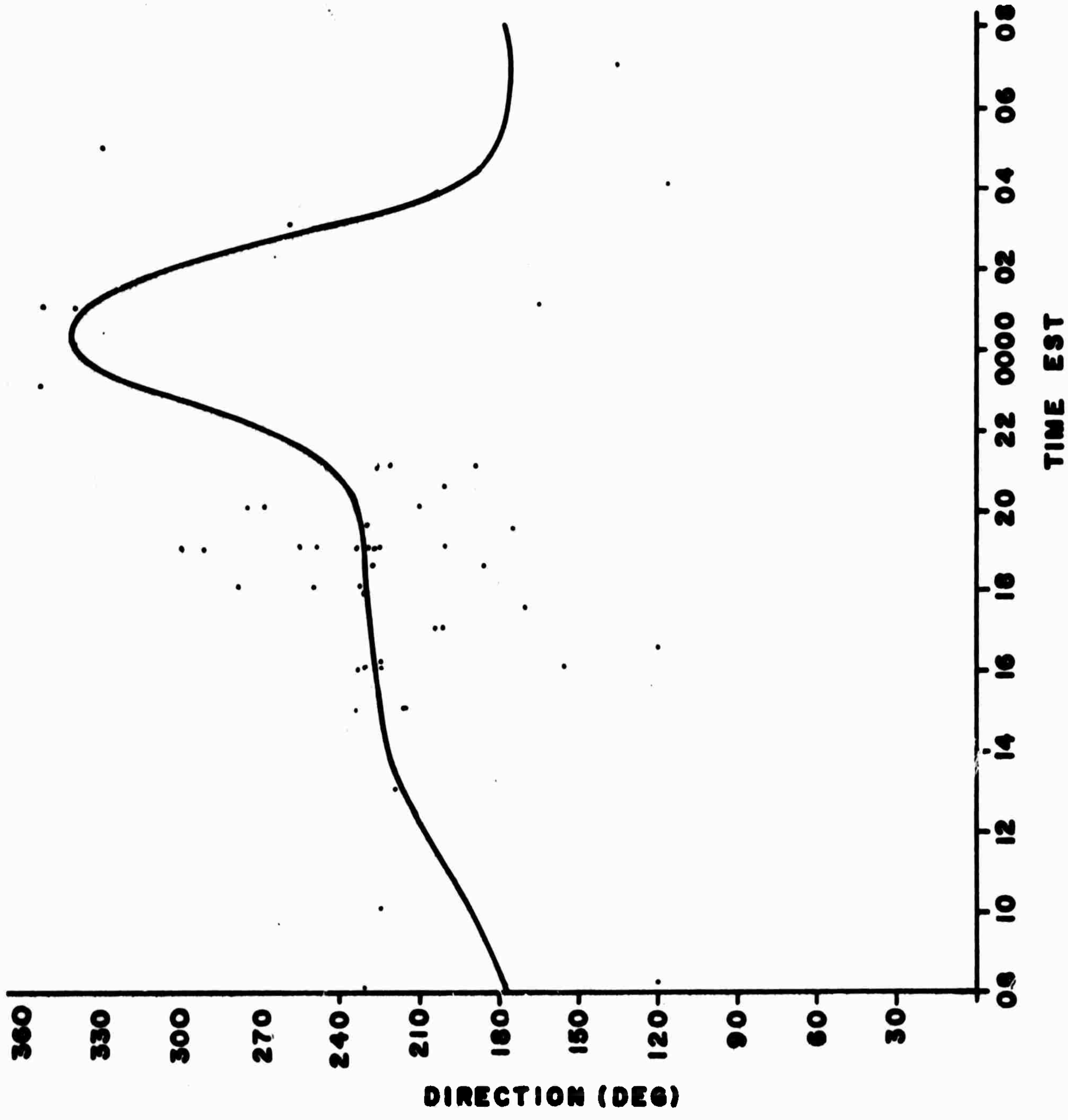

FIGURE 7. Diurnal variation of direction of heading of TID's.

of TID's. During the local times 1500 to 2000 hours where TID activity seems to be predominant, the TID direction also appears to be consistent. The direction in which TID's were heading during this interval of time was southwest to west. In other words, our investigation showed that the predominant direction of arrival for medium scale TID's at a Northern Hemisphere middle latitude station is in agreement with that of Jones (1969) and Davies and Jones (1971). It should be pointed out here that Munro, from an extensive study of medium scale TID's from a Southern Hemisphere station, Sydney, Australia, concluded that the predominant direction of travel was northeast to east.

Histograms for TID velocities for 20 m sec $^{-1}$ intervals were drawn as shown in Figure 8. It can be seen from this figure that the histogram peaks for the interval 140-160 m sec $^{-1}$. Minor, but equally important peaks were noticed for intervals 120-140 m sec $^{-1}$, 160-180 m sec $^{-1}$ and 200-220 m sec $^{-1}$. Histograms for TID directions for 20° intervals were also drawn as shown in Figure 9. From the histogram it can be seen that the direction of heading of TID's was mainly between 220°-240°. This investigation shows that the medium scale TID's have phase velocities in the range 140-200 m sec $^{-1}$ and the direction of arrivals are in between NE to E.

The following conclusions regarding the directions of medium scale TID's may be drawn from the results of the present investigation and those of earlier results (Chan and Villard, 1962; Davies, 1962; and Georges, 1967).

1. Near the solstices, disturbances in both hemispheres travel in approximately the same direction, away from the winter pole.
2. Near the equinoxes, disturbances in the Northern Hemisphere travel approximately in the westward direction, while those in the Southern Hemisphere travel eastward. Most of the earlier results

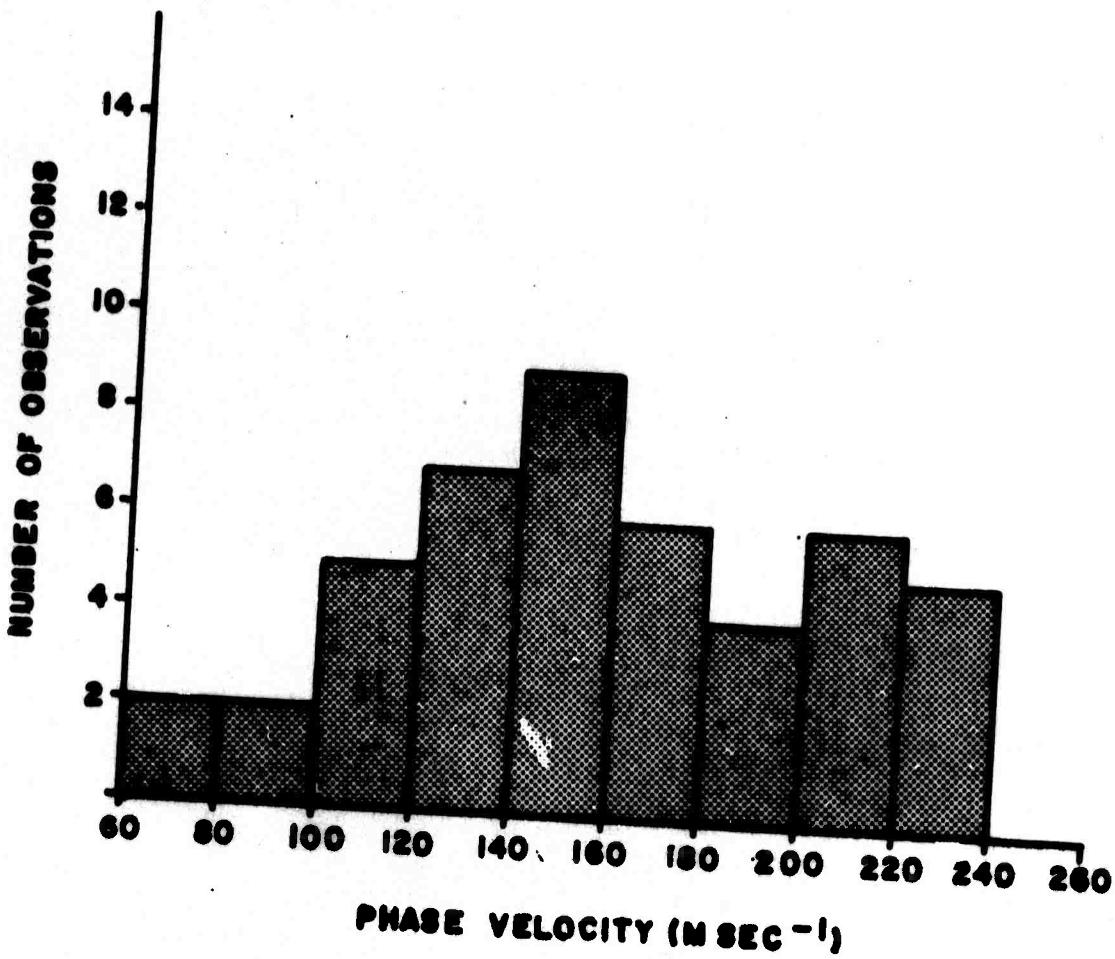

FIGURE 8. Histograms for TID phase velocities.

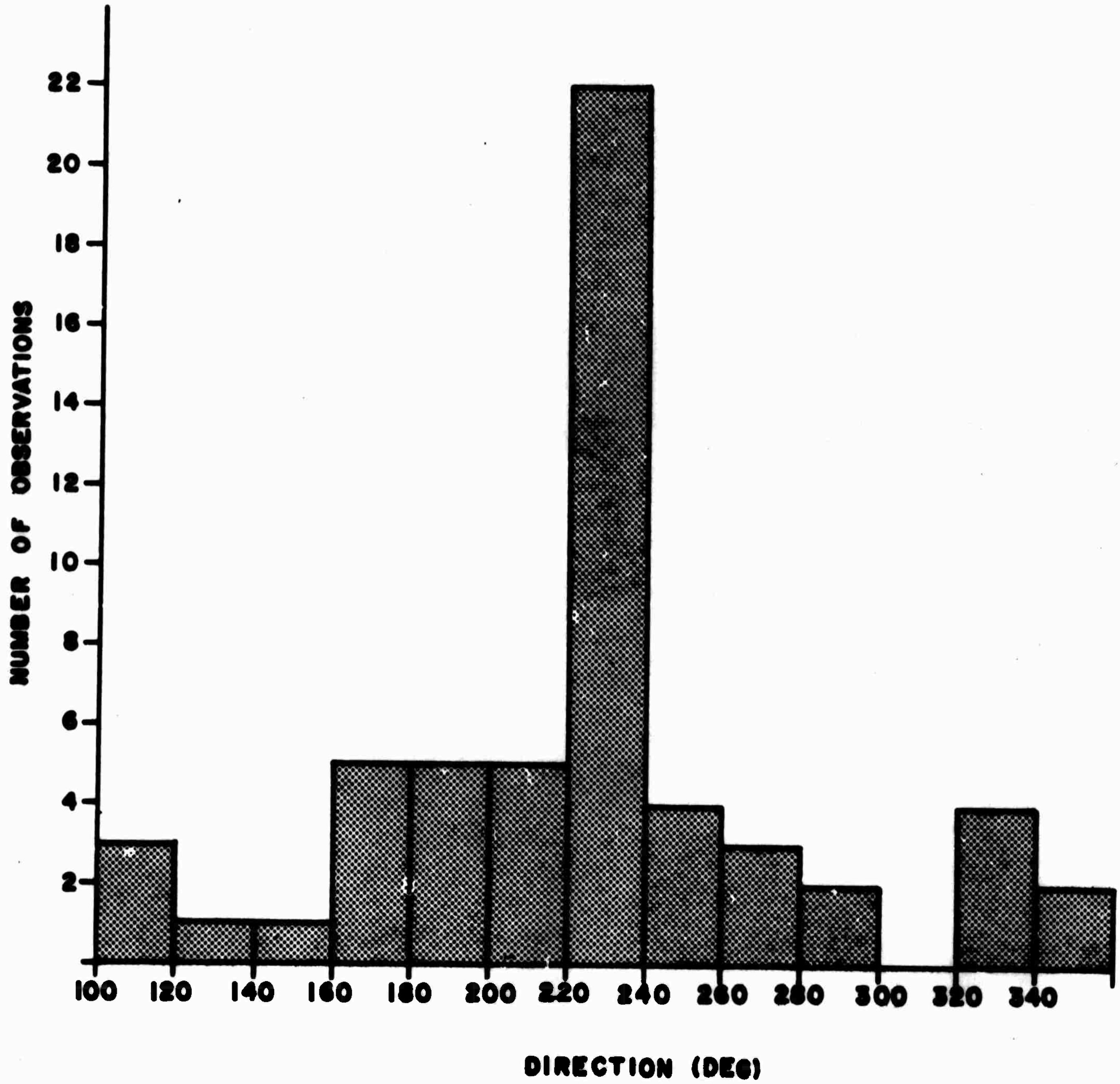

FIGURE 9. Histogram for TID heading direction.

support the first conclusion. The experimental evidence for the second conclusion comes from Jones (1969) and the results of the present investigation.

5.1 TID's and Internal Atmospheric Gravity Waves

TID's have been observed by several techniques by various investigators. However, it is still not clear what is the general nature of the travelling disturbance mechanism. It may be argued that winds in F region levels may act as transport mechanism. Winds at F region heights are not capable of moving ionization across geomagnetic field lines with any appreciable efficiency but they do impart to the ionization their component of velocity in the direction of the geomagnetic field. Horizontal winds moving with the speeds observed would thereby tend to raise or lower the whole F layer but no such unidirectional motion is observed. The vertical motion could be diminished by the effects of vertical polarization fields generated by the motion itself, but the degree of diminution is not appreciable at most latitudes. This shows that it is justified to argue against atmospheric winds as the transport mechanism.

Hydromagnetic waves of pertinent periods are likely to be strongly absorbed in the F region but these waves can probably be discounted on the basis of speed as they travel much faster than the observed disturbances. The Alfvén speed at 250 km is about 3300 m sec $^{-1}$, (Hines, 1960; Ovezgel'dyyev and Lezhneva, 1965). The chief attraction of the hydromagnetic hypothesis was its ability to explain the apparent downward progression of the disturbances as a direct consequence of generation at great height. This conflicts with experimental observation which indicated that disturbances in the F1 region are often not to be found in the F2 region above (Heisler, 1958).

Internal atmospheric gravity waves do appear to have the necessary characteristics to account for the behavior of travelling ionospheric disturbances (Hines, 1960). For an isothermal atmosphere at a height of 225 km, the shortest period of these oscillations would be around 12 - 15 min. If the energy of the wave were propagating upwards into the F region then it will ultimately be dissipated when viscous effects become large. The TID's seen in the F region which are not normally seen in the E region may be explained as a consequence of the exponential growth of the amplitude with height which characterizes internal gravity waves.

The energy of internal atmospheric gravity waves propagates upwards only in modes whose phase progression is downwards. This is in general agreement with experimental results on TID's. Davies and Jones (1971) made TID observations at Boulder (Lat. 40°N) using CW doppler (phase-path) sounders and the results were compared with the theory of atmospheric gravity waves. They calculated wave front tilts in the order of 30° - 50°. Georges (1968) also calculated wave front tilts for TID's whenever simultaneous ionograms were available. For most of the TID's the wave front tilts were in 30° - 60° which is in agreement with the theory of atmospheric gravity waves. For internal atmospheric gravity waves the wave front tilt with the vertical for an isothermal atmosphere is given by Tolstoy (1963).

$$\mathrm{Cos}\ \theta = T_B/T$$

where θ is measured clockwise from the vertical, T_B = Brunt-Väisälä period and T is the wave period. For a wave period of 20 minutes and Brunt-Väisälä period of 14 minutes, the tilt would be 45°, and for a 2-hour period it would be 83°. These are in agreement with experimentally observed ionospheric wave front tilts (Georges, 1968, Davies and Jones, 1971).

Munro's statistics on the occurrence, speeds and directions of several medium scale disturbances show a tendency of waves to come from the general direction of winter polar region. The characteristics of the medium scale TID's observed by the present investigation and those of Munro (1958) and Georges (1968) agree with Friedman's estimates with regard to size and wave front tilt (Friedman, 1966). According to Friedman (1966) the medium scale TID's may be explained in terms of imperfectly ducted internal atmospheric gravity waves whose maximum velocity is about 300 m sec $^{-1}$.

5.2 Internal Atmospheric Gravity Waves and Ionospheric Irregularities

Hines (1968) put forward rather strong arguments to explain some of the ionospheric phenomena as manifestation of internal atmospheric gravity waves. We discuss here the apparent correlation between TID's and sporadic E using gravity wave concepts.

Martyn (1959) tried to explain the formation of some types of E_s at low and middle latitudes by ionization inhomogeneities moving downward. Experimental data from ionosondes show that there exists some relationship between the F and E regions of the ionosphere (Fejer, 1959; Bowman, 1959). Ovezgel'dyyev and Korsunova (1964) and Ovezgel'dyyev and Vasil'yeva (1964) showed on the basis of data obtained in 1962, that in some cases the F_o layer observed in the F region, gradually changed into sporadic E layer. Generally it took about 2-3 hours for the secondary formation, which gradually changed into an E_s. It was also shown that the transformation of a secondary formation in the F region into an E_s was apparently independent of magnetic activity. The data also indicated that the process of transformation depended on the time of the day and season and to some extent on the solar activity level. Castel and Faynot (1964) observed from a study of ionograms that irregularities

first appear in the upper F region and move downward, producing weak sporadic E. We have investigated the occurrence of sporadic E ionization at times in which medium scale TID's are observed on the doppler records. Published ionogram data from Bellarica, Massachusetts (42.5°N 71.2°W, approximately the same latitude as our Catskill station) during the TID event days were examined for possible clues on the occurrence of sporadic E. We have noticed that in about 70% cases the sporadic E appeared after 3-4 hours of the passage of a TID. This result suggests some apparent connection between the passage of TID's and occurrence of sporadic E ionization.

The transformation of secondary ionization in the F region into E_s (Ovezgel'dyyev and Lezhneva, 1965) and the apparent relation between TID and sporadic E may be regarded as a particular case of vertically moving disturbances. Attempts to explain vertical motions of irregularities, using hydromagnetic wave concepts have not been successful for reasons mentioned earlier in the report. At this stage the mechanism responsible for the vertical motion remains obscure.

6. Discussion

Data corresponding to some of the TID events were subjected to power spectral analysis in order to find the dominant period of these events. The results are shown in Table 4. The reflection height of the probing frequency (4.824 MHz) was assumed to be around 200-220 km. For this height and for an isothermal atmosphere the acoustic cutoff period t_a and the Brunt-Väisälä period t_B are approximately 11.5 minutes and 12.5 minutes respectively (Chang, 1968). Figure 10 shows the distribution of the medium scale TID periods obtained in our investigation. All samples except two have periods longer than t_B, that is, the observed disturbances are within the frequency range of internal gravity waves.

TABLE 4

TID WAVE PARAMETERS

Date	Time (EST)	Phase Velocity (m sec^{-1})	Direction (deg.)	Period (min.)	Y Wavelength (km)
10-3-69	1730	150	170	12	108
10-5-69	1900	140	225	18	151
10-5-69	0000	284	346	10	170
10-8-69	2300	152	329	24	219
10-20-69	1700	170	222	18	184
10-20-69	1830	230	228	12	165
10-25-69	0500	73	333	18	79
10-25-69	1700	150	228	12	108
10-26-69	2100	345	226	16	313
10-28-69	1900	187	230	24	269
10-29-69	1830	180	235	12	130
10-31-69	0100	365	353	18	394
11-2-69	1600	165	235	12	119
11-3-69	0700	25	135	18	27
11-4-69	1500	200	235	18	216
11-7-69	0100	525	165	8	252
12-21-69	0730	140	50	9	76
2-5-70	1900	180	230	18	194

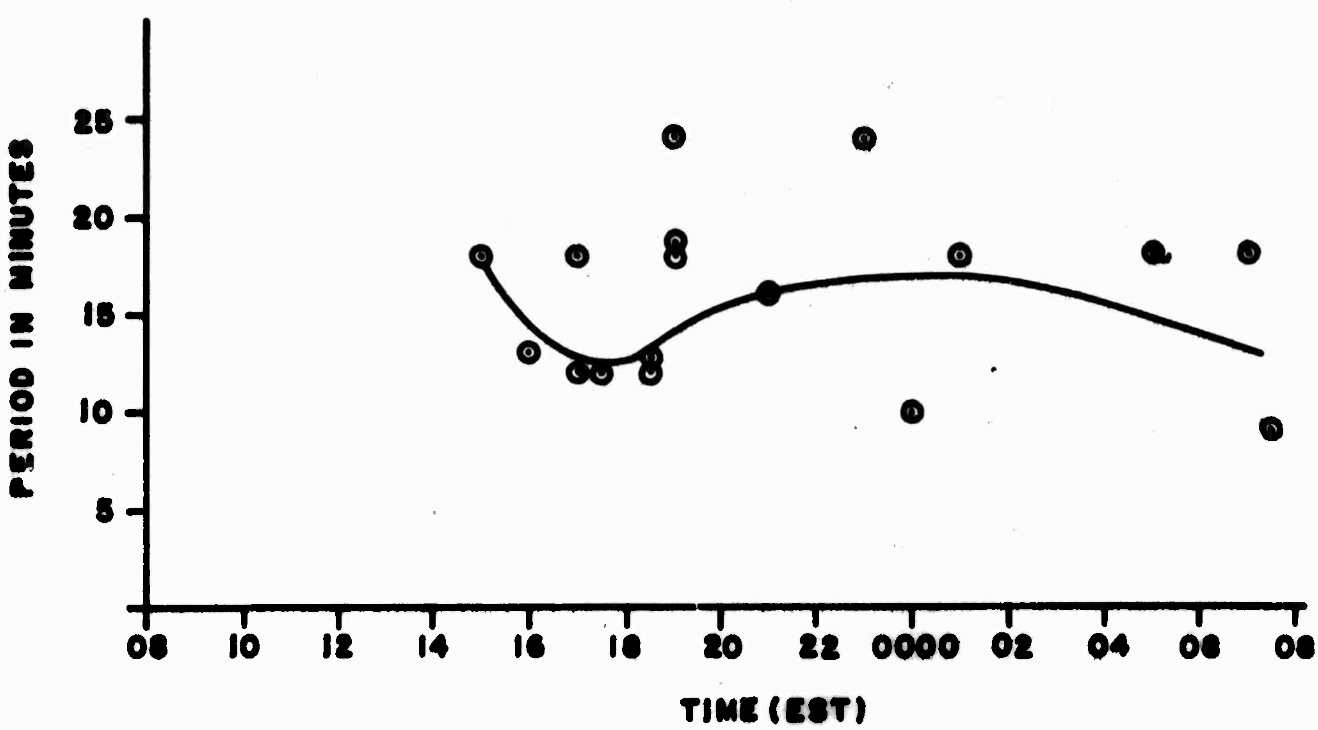

FIGURE 10. Distribution of TID periods.

However, since in the region between 90-250 km (where temperature begins to climb and molecular weight-scale height-changes) the acoustic cutoff period (t_a) can become greater than the Brunt-Väisälä period t_B (Johnston, 1967), direct separation between acoustic and internal modes is not possible, and we think more appropriate to call them acoustic gravity waves, as both buoyancy and elastic forces are tightly coupled in this region.

Tolstoy (1970) when discussing geoacoustic mode structure, atmospheric parameters and nuclear atmospheric tests, pointed out the importance of investigations of TID's and their dispersion characteristics as means to obtain information about the variation of the neutral structure at ionospheric levels. We want to add here that the existence and evaluation of the dispersion of TID's can also provide information on the origin of ionospheric irregularities.

Hines (1968) argued that if the case for a gravity wave interpretation for TID's is accepted, then it is natural to extrapolate the interpretation downward: the waves are believed to be propagating upwards to the F region levels producing TID's. In their way up the waves travel through the region of E_s occurrence. Also the wave spectrum must be broader at the lower levels since dissipation is less severe there. The combined effect of filtering action of dissipative forces and wind shears probably can account to some extent for the apparent correlation between TID's and sporadic E ionization.

Identification of sources for naturally occurring wave trains is still a problem, since several are likely to be involved. Auroral infrasonic waves, auroral electrojets were shown to be sources for large scale TID's (Hunsucker and Tveten, 1967; Liszka and Taylor 1965). Severe local weather disturbances were suggested as sources for high frequency fluctuations in F region levels (Davies and Baker, 1969; Georges, 1968). Earthquakes, jet streams,

irregular mesopheric winds were also suggested as potential sources for generation of TID's.

An attempt was made in this report to study the medium scale travelling wave disturbance characteristics for a Northern Hemisphere middle latitude array of stations. The results were in general agreement with the earlier investigations and support the interpretation that the TID characteristics can be successfully explained using internal atmospheric gravity wave concepts.

7. Summary and Conclusions

Travelling ionospheric disturbances (TID's) in the ionized regions of the earth's upper atmosphere were investigated using a CW doppler (phase-path) sounding array. The following conclusions can be drawn from the results of the present investigation.

1. Near the solstices, disturbances in both hemispheres travel approximately in the same direction, away from the winter pole.
2. Near the equinoxes, disturbances in the Northern Hemisphere travel approximately in the westward direction, while those in the Southern Hemisphere travel eastward.
3. The propagation parameters of the observed disturbances such as the phase speeds, wavelengths and periods are in general similar to the parameters of acoustic gravity waves and hence it may be concluded that the TID's are manifestations of atmospheric acoustic gravity waves propagating in the upper atmosphere. The observed directions of medium scale TID's travelling away from winter polar regions, suggest that these disturbances were generated in the polar regions. Some support for this conclusion is found in observations of mesospheric heating

in the winter polar region (Maeda and Young 1966), since gravity wave energy penetrates upwards much more easily in the absence of mesospheric temperature decline (Friedman 1966). Also the observed characteristics of TID's fit Friedman's theory (1966) with regard to speed and wave front tilts.

4. Study of ionograms showed that the ionospheric irregularities first appeared in the upper F region and moved downward producing weak sporadic E ionization. The investigation on medium scale TID occurrence time and appearance of sporadic E showed that in about 70% of the cases studied the sporadic E appeared after 3-4 hours of the passage of a TID. The apparent connection between a passage of a TID and the occurrence of sporadic E ionization can not be satisfactorily explained using hydromagnetic wave theory, since hydromagnetic waves travel much faster than the observed disturbances. The other alternative to explain these phenomena is to look for an acoustic gravity wave interpretation as these waves travel much slower than hydromagnetic waves. The combined effects of filtering action of dissipative forces and wind shears probably can account to some extent for the apparent correlation between TID's and sporadic E ionization.

The investigation on TID's has shown that the disturbances are highly dispersive in nature. No attempt was made to study the dispersion characteristics of TID's. Recently Tolstoy (1970) suggested that the dispersion studies of TID's could provide a valuable tool to estimate atmospheric structure parameters in the ionospheric levels. To conclude we would like to point out that during the experimental phase of this project very valuable data on TID's has been collected and a further analyses of the data is highly desirable to investigate the atmospheric structure at ionospheric levels.

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